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Application of Rapid Prototyping to the Investment Casting of Test Hardware (MSFC Center Director's Discretionary Fund Final Report, Project No. 98–08)

K.G. Cooper and D. Wells
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

June 2000

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LIST OF ACRONYMS

3DP	three-dimensional printing
ABS	acrylonitrile butadiene styrene
CAD	computer-aided design
FDM	fused deposition modeling
IITRI	IIT Research Institute
LOM	laminated object manufacturing
MM2	Model Maker II
MSFC	Marshall Space Flight Center
RP	rapid prototype
SLA	stereolithography
SLS	selective laser sintering

TECHNICAL MEMORANDUM

APPLICATION OF RAPID PROTOTYPING TO THE INVESTMENT CASTING OF TEST HARDWARE (MSFC Center Director's Discretionary Fund Final Report, Project No. 98–08)

1. PURPOSE

The objective of this project is to evaluate the capabilities of various rapid prototyping processes and produce quality test hardware grade investment casting models. Of the modeling processes being utilized, all six are currently used in-house at Marshall Space Flight Center (MSFC), one of which was acquired through this program. The processes include the following:

- DTM Corp. selective laser sintering (SLS)
- Stratasys fused deposition modeling (FDM)
- 3D Systems stereolithography (SLA)
- Helisys laminated object manufacturing (LOM)
- Sanders Model Maker II (MM2)
- Z-Corp three-dimensional printing (3DP).

2. BACKGROUND/APPROACH

Investment casting masters of a selected propulsion hardware component, a fuel pump housing, were rapid prototyped on the several processes in-house, along with the new Z-Corp process acquired through this project. Also, tensile samples were prototyped and cast using the same significant parameters. The models were then shelled in-house using a commercial grade zircon-based slurry and stucco technique. Next, the shelled models were fired and cast by our in-house foundry contractor (IITRI), with NASA–23, a commonly used test hardware metal. The cast models are compared by their surface finish and overall appearance; i.e., the occurrence of pitting, warpage, etc., as well as dimensional accuracy.

3. TEST RESULTS

Eight copies of the fuel pump model in figure 1 were slated to be fabricated, shelled, and cast by the end of this project. The following segment contains data for each of the models attempted, listed by the rapid prototyping build process and initial pattern material. Data are summarized in the tables at the end of this section. Six of the eight models made it through the casting phase whereas two did not. The part was not scaled in anticipation of casting shrinkage, which is reflected in the resulting dimensional data.

Explanations will be given within the proper segment for each resulting casting. Descriptive photographs of the different flaw terminology are shown in appendix A. Dimensional data were taken in three axes with respect to the orientation of the part during rapid prototype (RP) pattern fabrication. Dimensions are given in inches over the entire part, with inch per inch accuracy in parentheses.

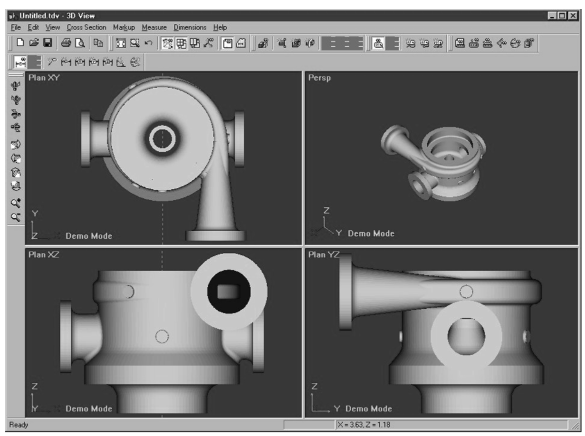

Figure 1. The Fastrac 60K fuel pump housing was used as the baseline pattern.

3.1 Selective Laser Sintering—Polycarbonate Material

The SLS-polycarbonate material was a precursor to the current preferred casting pattern material of the SLS process, and was fabricated at MSFC in the Sinterstation 2000 device. The casting pattern fabricated showed a dimensional accuracy of ≈ 0.010 in. (0.002 in./in.) over the entire part in the x and y dimension, with significant accuracy in the z, or height dimension, of 0.003 in. (0.0008 in./in.) (see table 1). A significant amount of accuracy was lost from the pattern to the casting due to shrinkage via cooling of the metal casting. The maximum out-of-tolerance in the z dimension was 0.0529 in. (0.0124 in./in.) over the entire part height.

Table 1. SLS polycarbonate dimensional analysis.

SLS-Polycarb	x Accuracy	y Accuracy	z Accuracy	x Per Inch	y Per Inch	z Per Inch
CAD-RP	–0.0105	–0.0090	0.0032	–0.0022	–0.0015	0.0008
RP-Casting	0.0439	0.0301	0.0496	0.0094	0.0049	0.0116
CAD-Casting	0.0334	0.0211	0.0529	0.0071	0.0034	0.0124

The surface finish obtained had a grainy texture, due to the large standard particle size of the powder used for fabrication, which was picked up in the final metal casting as well. The surface finish of the final casting is ≈ 200 µin. There were no shell inclusions except for one chip in the lower thin rim. This finish may require some final machining or polishing, depending on the application requirements. The polycarbonate, per conclusion of this test, is therefore best suited for quick concept castings with lenient dimensional and surface requirements, similar to a sand casting.

3.2 Selective Laser Sintering—Trueform Polyamide

SLS-Trueform polyamide is the next generation casting material following polycarbonate. This pattern was also fabricated in the Sinterstation 2000 at MSFC and showed significant dimensional stability improvements over the SLS polycarbonate material. From table 2, the x and y dimensions were within 0.002 in. (0.0004 in./in.) tolerance and the z height held a tolerance of 0.007 in. (0.0016 in./in.). The surface finish was also significantly better, with sharper edges and a smoother texture than the polycarbonate. Shell burnout was much easier than with polycarbonate, with less ash content and a lower furnace cycle time. The final as-cast dimensional properties of the Trueform casting were also excellent, with maximum out-of-tolerance in the z height dimension of 0.0155 in. (0.0036 in./in.). The surface finish was near 60 µin. with slight pitting due to shrinkage and ceramic slurry inclusions.

Table 2. SLS-Trueform polyamide dimensional analysis.

SLS-Trueform	x Accuracy	y Accuracy	z Accuracy	x Per Inch	y Per Inch	z Per Inch
CAD-RP	–0.0020	–0.0010	–0.0070	–0.0004	–0.0002	–0.0016
RP-Casting	0.0104	0.0046	0.0225	0.0022	0.0008	0.0053
CAD-Casting	0.0084	0.0036	0.0155	0.0018	0.0006	0.0036

3.3 Fused Deposition Modeling—Investment Casting Wax

The FDM investment casting wax model (fig. 2 and table 3) was initially slated to be fabricated at MSFC; however, technical difficulties with the on-site equipment would not allow for it within the allotted timeframe. In response, the vendor fabricated a model on an FDM–2000 at their facility to make up for the downtime experienced during the on-site equipment upgrade. The results herein are therefore determined from that model (fabricated by the vendor of the FDM system), which was then shelled and cast on site at MSFC in the same manner as the other specimens.

The wax pattern showed good dimensional tolerance, with a maximum discrepancy in the *x* dimension of 0.0077 in. (0.0017 in./in.). The surface finish was very smooth, at 60 μin., due to an apparent thin wax coating applied by the vendor. There were, however, a few minor inclusions and scabs due to ceramic slurry defects. The shell burnout was very simple and event-free, with no remaining ash content or shell disruption. Final as-cast dimensional properties revealed a maximum out-of-tolerance of 0.017 in. (0.004 in./in.), which was measured in the *z* dimension of the part.

Figure 2. FDM wax pattern prior to shelling.

Table 3. FDM investment casting wax dimensional analysis.

FDM-Wax	*x* Accuracy	*y* Accuracy	*z* Accuracy	*x* Per Inch	*y* Per Inch	*z* Per Inch
CAD-RP	0.0077	0.0003	0.0035	0.0017	0.0000	0.0008
RP-Casting	0.0006	0.0034	0.0135	0.0001	0.0006	0.0032
CAD-Casting	0.0084	0.0036	0.0170	0.0018	0.0006	0.0040

3.4 Laminated Object Manufacturing—High-Performance Paper

The LOM high-performance paper model (fig. 3) was fabricated on the LOM–1015 machine at MSFC (see table 4). The pattern dimensions showed a maximum tolerance discrepancy in the *z* dimension of 0.0293 in. (0.0069 in./in.). There was a maximum variation from pattern to casting in the *y* dimension of 0.030 in. (0.0049 in./in.), yet the shrinkage in the casting actually brought the final part back into close proximity of the original computer-aided design (CAD) data. The final as-cast dimensions revealed a maximum out-of-tolerance of only 0.0187 in. (0.0031 in./in.).

The shell burnout did require extra attention for ash removal, although a light wax coating applied to the model prior to shelling reduced this significantly. Still, some cracking was noticeable in the shell after burnout, therefore the shell was again dipped in the slurry in an attempt to patch it. This approach was partially successful in that a final casting was achieved with a 60-μin. surface finish in most areas. There were “rat tails,” however, on the casting due to metal seeping outward into some of the unfilled cracks in the shell. These can be removed by postmachining techniques and really do not pose a problem.

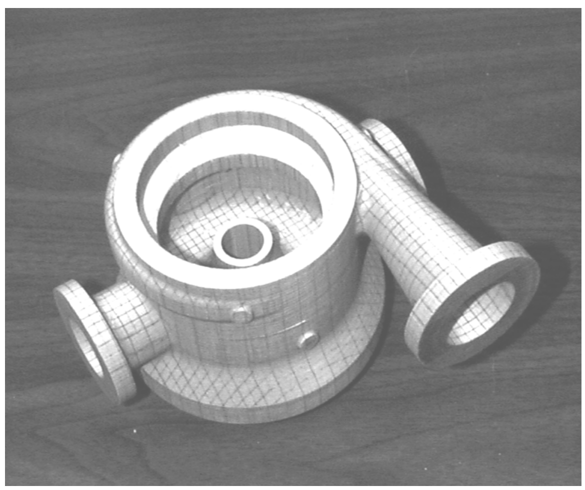

Figure 3. LOM pattern prior to shelling.

Table 4. LOM paper dimensional analysis.

LOM	*x* Accuracy	*y* Accuracy	*z* Accuracy	*x* Per Inch	*y* Per Inch	*z* Per Inch
CAD-RP	0.0130	–0.0113	–0.0293	0.0028	–0.0018	–0.0069
RP-Casting	0.0003	0.0300	0.0286	0.0001	0.0049	0.0067
CAD-Casting	0.0132	0.0187	–0.0006	0.0028	0.0031	–0.0001

3.5 Three-Dimensional Printing—Starch (Cellulose)

The 3DP pattern (fig. 4) was fabricated at MSFC with the Z402 3D printer system. Not unlike the other techniques, the major out-of-tolerance in the pattern was found in the *z* dimension at 0.0142 in. (0.0014 in./in.). The as-cast dimensional analysis revealed the major out-of-tolerance, again in the *z* dimension, of 0.0543 in. (0.0127 in./in.).

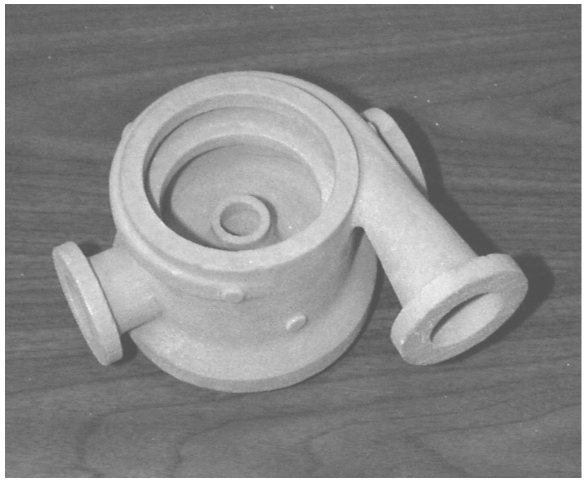

Figure 4. 3DP pattern prior to shelling.

The 3DP pattern burnout was clean, likened unto using a wax pattern. The final surface finish of the casting was ≈300 μin., with only a few surface inclusions and shrink pits. It was expected, due to the economical advantage of the 3DP process, that the castings would be somewhat rougher than more expensive processes, which turned out to be the case here. These patterns will provide faster, less expensive alternatives to acquire near-net-shape castings (see table 5).

Table 5. 3DP starch dimensional analysis.

Z-Corp	*x* Accuracy	*y* Accuracy	*z* Accuracy	*x* Per Inch	*y* Per Inch	*z* Per Inch
CAD-RP	0.0065	–0.0085	0.0142	0.0014	–0.0014	0.0033
RP-Casting	0.0142	0.0349	0.0400	0.0030	0.0057	0.0094
CAD-Casting	0.0207	0.0264	0.0543	0.0044	0.0043	0.0127

3.6 Fused Deposition Modeling—ABS Plastic

The FDM acrylonitrile butadiene styrene (ABS) model (fig. 5) was fabricated on the FDM–1600 machine at MSFC. Like the FDM wax model, the ABS model held good tolerances with a porosity, which allowed ceramic shell inclusion, sometimes completely through the thin planar sections of the component. Also, there was some shell cracking due to expansion of the material, which allowed some small "rat tails" in the casting where the molten metal flowed out into the cracks. Other than these problems, which could be corrected with pattern treatment, the majority of the surface finish was acceptable at 60 μin. (see table 6).

Figure 5. The FDM-ABS model as fabricated at MSFC.

Table 6. FDM-ABS dimensional analysis.

FDM-ABS	*x* Accuracy	*y* Accuracy	*z* Accuracy	*x* Per Inch	*y* Per Inch	*z* Per Inch
CAD-RP	0.0068	0.0003	0.0035	0.0015	0.0000	0.0008
RP-Casting	0.0055	0.0125	–0.0116	0.0012	0.0020	–0.0027
CAD-Casting	0.0132	0.0128	–0.0081	0.0028	0.0021	–0.0019

3.7 Stereolithography—Epoxy 5170

An SLA epoxy pattern was made for this test with the vendor-recommended internal corrugated structure on the SLA–250 system at MSFC. The pattern had good dimensional tolerance and surface finish; however, in the late casting phases of the project, the pattern broke the shell during burnout due to excessive expansion. There are several possible causes for the expansion, including the incomplete drainage of extra resin from inside the part cavity, improper temperature ramping during burnout, and the lack of high-oxygen burnout capability in the furnace.

It should be noted that some foundries with the proper facilities and training experience very good results with SLA patterns; therefore, the model failure in this test was not due to a bad model.

3.8 Model Maker II—Investment Casting Resin

Investment casting resin model fabrication was begun on the MM2 system at MSFC, but was discontinued due to repeated equipment failure. The machine was recalled at this time for upgrades and repairs, but was not returned in time to finish this experiment. In addition, the model file was sent to the vendor for fabrication, which was again unsuccessful. The determining cause was concluded to be the excessive size of the part as compared to the capabilities of the equipment itself.

It should be noted that the MM2 systems create very accurate casting models for much smaller size components than those used during this test.

3.8.1 Cost Comparisons

Table 7 shows the final costs estimated for each completed casting compared with quoted figures for the same pattern fabricated by sand casting and machining. These figures included all associated expenditures from the point when the CAD file was received to the final castings and cleanup. A detailed table showing all of the variables concerned is given in appendix B.

Table 7. Summarized costs associated with each prototyped casting.

Process	Cost ($)
SLS-Polycarb	1,666
SLS-Trueform	1,616
FDM-Wax	1,765
FDM-ABS	1,840
LOM	2,005
Z-Corp	1,116
Sand Casting	20,000
Machined From Plate	65,000

4. CONCLUSIONS

Figure 6 shows the final as-cast patterns prior to gate-and-riser removal and post cleanup. Although the final cast hardware components from each rapid prototyping process were of varying degrees of success, each proved a significant cost advantage over conventional manufacturing techniques. The SLS-Trueform model provided the most acceptable casting, followed by FDM-Wax. Interestingly enough, these parts were in the intermediate cost range (see table 7), although the SLS pattern built 15 times faster than the FDM pattern (4 hr versus 65 hr). This was due to a direct inverse proportion between the per pound cost of the build materials and the cost of the machine run times.

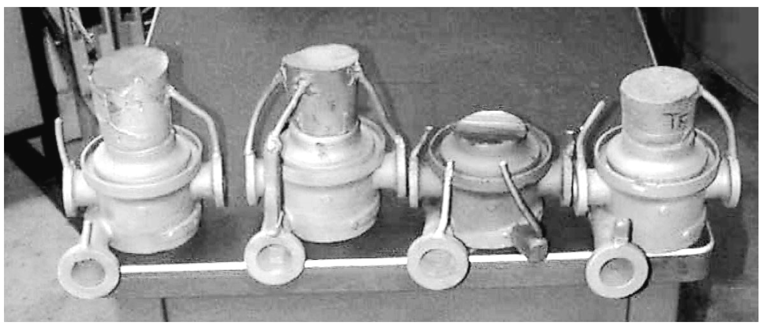

Figure 6. As-cast hardware prior to final cleanup.

The least expensive model was the Z-Corp pattern, which also was the fastest to complete at 3.5 hr, and also one of the least accurate. The Z-Corp patterns will be more suitable for initial prototype castings, or especially castings that are designed for moderate final machining process; i.e., near-net-shape castings.

This project was completed in the proposed time and budget allocations originally set.

5. RECOMMENDATIONS

The rapid prototyping and casting teams recommend a followup study, focusing on the two best techniques as found by this research. The followup would be directed toward applying these processes to various different geometries, as well as fine-tuning the gating, shelling, and casting aspects at MSFC to accommodate these materials better for future hardware fabrication needs.

APPENDIX A—DESCRIPTIONS AND PHOTOGRAPHS OF INVESTMENT CASTING DISCREPANCIES

A.1 Slurry Inclusions

Slurry inclusions (also referred to as inclusions) are rough patches, sometimes even holes, in the castings which are caused by the initial coats of slurry "wicking" into unsealed voids or porous material. These produce needle-like projections or bumps on the inside surface of the shell (postfired) that are then replicated as holes in the final casting. Figure 7 shows a typical slurry inclusion area, as seen on one of the castings in this study.

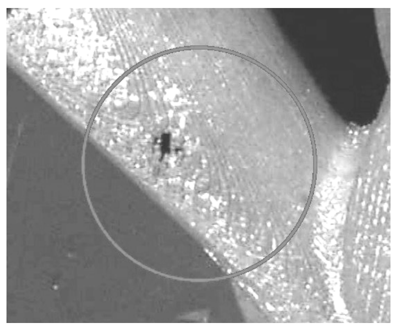

Figure 7. Slurry inclusion area on FDM-ABS casting.

A.2 Rat Tails

Rat tails are thin protruding vanes of metal on the casting surface that are caused by shell cracking during burnout. Shells crack for various reasons including excessive moisture buildup and overexpansion of the pattern. Although the shell sometimes will completely rupture due to cracking, more often it will just leave these small crevices throughout the shell. When the molten metal is poured into the shell during the casting process, it is allowed to flow out and fill up all of these cracks, thus resulting in protrusions on the final casting surface. Rat tails are much preferred over inclusions or shrinkage, as the excess material can be removed easily by finishing. Figure 8 shows an example of a rat tail.

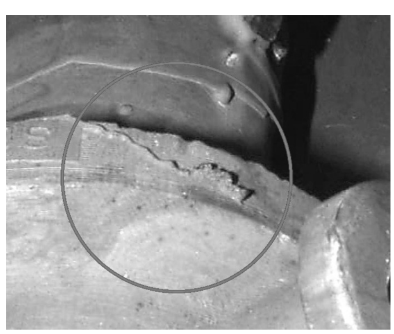

Figure 8. Rat tails found on LOM casting.

A.3 Shrinkage

Shrinkage in this report refers to larger voids left in the castings, often rendering the final components unusable. Shrinkage often occurs in thinner areas of a casting, which are adjacent to a dense section of the part. Although the complete area may be filled with the molten metal during casting, the cooling of the denser section occurs more slowly, thus “pulling” material away from the thinner areas. This is a common casting problem, which is confronted by allowing additional vents from strategic areas to give them more material to feed from during cooling. Figure 9 shows an example of shrinkage.

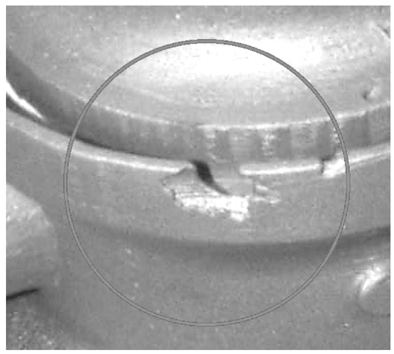

Figure 9. Shrinkage found on SLS casting.

APPENDIX B—VARIABLES ASSOCIATED WITH COST ESTIMATION OF RAPID PROTOTYPING CASTINGS

RP Process	SLS-Poly	FDM-Wax	SLS-True	LOM	FDM-ABS	3DP-Z
RP PROGRAMMING						
Labor time, hr	2.0	0.5	2.0	1.0	0.5	0.3
Labor rate, $/hr	$50	$50	$50	$50	$50	$50
Machine time, hr	0.0	0.0	0.0	0.0	0.0	0.0
Machine rate, $/hr	$0	$0	$0	$0	$0	$0
Material cost, $	$0	$0	$0	$0	$0	$0
Overall step time, hr	2.0	0.5	2.0	1.0	0.5	0.3
Subtotal, $	$100	$25	$100	$50	$25	$13
RP MODEL PRODUCTION						
Labor time, hr	4.0	1.0	4.0	4.0	1.0	0.5
Labor rate, $/hr	$50	$50	$50.0	$50	$50	$50
Machine time, hr	4.0	65.0	4.0	30.0	65.0	3.5
Machine rate, $/hr	$44	$10	$44	$18	$10	$28
Material cost, $	$125	$100	$175	$75	$100	$40
Overall time, hr	8.0	66.0	8.0	34.0	66.0	4.0
Subtotal, $	$501	$800	$551	$815	$800	$163
SETTING UP MOLD						
Labor time, hr	0.5	0.5	0.5	0.5	0.5	0.5
Labor rate, $/hr	$50	$50	$50	$50	$50	$50
Machine time, hr	0.5	0.5	0.5	0.5	0.5	0.5
Machine rate, $/hr	$100	$100	$100	$100	$100	$100
Material cost, $	$100	$100	$100	$100	$100	$100
Overall time, hr	1.0	1.0	1.0	1.0	1.0	1.0
Subtotal, $	$175	$175	$175	$175	$175	$175
SHELLING						
Labor time, hr	0.0			1.0		
Labor rate, $/hr	$50					
Machine time, hr	0.0			1.0		
Machine rate, $/hr	$100					
Material cost, $	$100					
Overall time, hr	0.0			2.0		
Subtotal, $	$100					
INVESTMENT BURNOUT						
Labor time, hr	1.0	0.5	1.0	1.5	1.0	0.5
Labor rate, $/hr	$50	$50	$50	$50	$50	$50
Machine time, hr	2.5	1.5	1.5	3.0	2.0	1.5
Machine rate, $/hr	$100	$100	$100	$100	$100	$100
Material cost, $	$100	$100	$100	$100	$100	$100
Overall time, hr	0.0	0.0	0.0	0.0	0.0	0.0
Subtotal, $	$400	$275	$300	$475	$350	$275

Variables Associated With Cost Estimation of Rapid Prototyping Castings (Continued)

RP Process	SLS-Poly	FDM-Wax	SLS-True	LOM	FDM-ABS	3DP-Z
INVESTMENT FIRING						
Labor time, hr	0.0			1.0		
Labor rate, $/hr	$50					
Machine time, hr	0.0			1.0		
Machine rate, $/hr	$100					
Material cost, $	$100					
Overall time, hr	0.0					
Subtotal, $	$100					
CASTING						
Labor time, hr	2.0					
Labor rate, $/hr	$50					
Machine time, hr	4.0					
Machine rate, $/hr	$20					
Material cost, $	$10					
Overall time, hr	0.0					
Subtotal, $	$190					
CLEANUP						
Labor time, hr	0.0			1.0		
Labor rate, $/hr	$50					
Machine time, hr	0.0			1.0		
Machine rate, $/hr	$100					
Material cost, $	$100					
Overall time, hr	0.0				2.0	
Subtotal, $	$100					
Labor time, hr	9.5	4.5	9.5	9.0	5.0	3.8
Overall time, hr	11.0	67.5	11.0	36.0	67.5	5.3
Subtotal, $	$1,666	$1,765	$1,616	$2,005	$1,840	$1,116

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13. ABSTRACT *(Maximum 200 words)*
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